VOLUME 79 SEPARATE No. 233

PROCEEDINGS

AMERICAN SOCIETY
OF
CIVIL ENGINEERS

AUGUST, 1953

DETERMINATION OF RADII OF CURVATURE OF TAXIWAYS

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AIR TRANSPORT DIVISION

{Discussion open until December 1, 1953}

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Printed in the United States of America

Headquarters of the Society
33 W. 39th St.
New York 18, N. Y.

PRICE $0.50 PER COPY

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This paper was published at 1745 S. State Street, Ann Arbor, Mich., by the American Society of Civil Engineers. Editorial and General Offices are at 33 West Thirty-ninth Street, New York 18, N. Y.

DETERMINATION OF RADII OF CURVATURE OF TAXIWAYS

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Objective

Consultation with the Airport Engineering Division of the U. S. Civil Aeronautics Administration early in 1951 brought out the lack of quantitative information on the relationship of aircraft speed to the radius of turning while taxiing. This relationship is an important consideration in the layout of taxiways, particularly those used for clearing aircraft from runways.

In order to increase the rate at which aircraft can land at the busier terminals, taxiway patterns must be developed which will permit minimum occupancy of runways by landing aircraft. This led airport designers to the concept of "lead-off taxiways" which would permit aircraft to leave the runway at speeds as high as 50 mph. Studies conducted by the Civil Aeronautics Administration[a] indicate suitable positions for lead-off taxiways along the runways. The present investigation, which complements the work of the CAA, provides information on suitable radii for these lead-off taxiways.

Apparatus

Three models of aircraft were used in these tests; the DC-3 and DC-6, manufactured by the Douglas Aircraft Corp. and the Convair-340 manufactured by the Consolidated-Vultee Aircraft Corp. These aircraft, shown in Fig. 1, are currently used for commercial operations throughout the world. Maximum gross take-off weights for these aircraft are: DC-3, 25,000 lb; Convair-340, 47,000 lb; and DC-6, 92,000 lb.

These aircraft are equipped with two types of landing gear: the nose-wheel type on the Convair-340 and the DC-6, and the tail-wheel type, on the DC-3. Main landing gear of the Convair-340 and the DC-6 are equipped with dual wheels; the DC-3 has single-tire main wheels. The principal dimensions of the landing gears are shown in Fig. 2.

The equipment used to determine the paths and speeds of the aircraft consisted of a 16 mm motion picture camera mounted on an outrigger extending from the cockpit window on the right-hand side of the aircraft as shown in

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a. U. S. Civil Aeronautics Administration, Office of Airports, Airport Engineering Bulletin No. 1. "Preliminary Report on Airport Configuration Studies". June 15, 1951.

Fig. 3. A grid formed of 20x20-ft squares was painted on the north-west end of the NW-SE runway at the San Francisco International airport as detailed in Fig. 4. The camera was adjusted to photograph vertically downward and thus record the path of the aircraft as it maneuvered over the grid. The camera was operated at a nominal speed of 32 frames per second, but the exact speed was determined by photographing a stop-watch.

Test Program

The test program was designed to indicate how aircraft speed, type of landing gear, total angle of turn, and passenger comfort imposed limits on the turning radius. An initial series of tests was sufficient, however, to show that speed is the only one of these variables having a significant effect on minimum permissible radius. This limiting speed was taken as that of impending skid and was determined by pilot judgment, although the observer riding in the aircraft was often able to note such confirming symptoms of impending skid as nose-wheel chatter or tail-wheel bounce, and tire squeal, while outside, the condition was implied by tire marks on the pavement.

The methods of steering the aircraft differed for the two types of land gear. The tail-wheel aircraft, DC-3, was steered by the use of wheel-brakes, engines, and rudder, in various combinations. The Convair-340 and the DC-6 were steered exclusively by means of the nose wheel.

The aircraft were taxied on the grid a total of 57 times at ground speeds ranging from 16 to 53 mph. For each run at impending skid, the path of the aircraft was recorded by the motion-picture camera. During the tests the winds were usually less than 15 mph.

Observations of the aircraft from the ground by visual and photographic means indicated a negligible amount of "body roll" even during the tightest turns.

Analysis of Data

The photographs of the aircraft's travel over the grid were viewed as still pictures. Each time the center of the camera crossed a grid line, the ground position of the camera with respect to an intersection of grid lines was plotted on a drawing of the grid. The relative positions of camera and landing gear being known, the path of the landing gear could be plotted on the drawing as shown in Figs. 5 and 6. In this manner the path of the turning aircraft was established. The radii of curvature were determined from the circular arcs which were used to fit smooth curves to the plotted points. The speed of the aircraft was readily determined from the number of exposed frames of film between crossings of grid lines and known camera timing in terms of frames per second. The paths of each aircraft at the impending skid condition for three different average speeds are shown in Figs. 7, 8, and 9. From these and similar plots the speed of the aircraft and the radius of curvature were obtained. The observed paths of the aircraft were best approximated by three- or four-centered compound curves though the actual curves were probably circular arcs with spirals at each end.

The data were plotted from the observed radius and the corresponding speed for each run at the impending skid condition, as shown in Fig. 10.

Upon fitting various curves to these data, it was found that a curve representing the fundamental equation of radial force opposed by frictional force used in the design of highway curves was entirely satisfactory. This equation

is

$$\frac{Wv^2}{gR} \text{ (the radial force)} = Wf \text{ (the opposing friction)}$$

Where W is weight, v is velocity, g is the acceleration of gravity, R is radius, and f is the friction factor[b]. When this equation is solved for R in feet, with v in miles per hour, it becomes

$$R = \frac{v^2}{15f}$$

It is recognized that this equation is not strictly applicable to the case of an aircraft because the weight in the term Wf is reduced by whatever lift the plane happens to have at a particular speed, while the mass term W/g on the other side of the equation remains unaffected. On the other hand as an aircraft turns off from a runway the wind creates a force opposite to the outward radial force which may partially offset the effect of lift. Other factors, such as distribution of load on the landing gear and tire condition may also have their effect. Nevertheless, the curve expressed by friction factor of 0.26, shows a good fit, well within the practicable limits of accuracy of the measurements, and represents the observed limiting condition for operation on dry bituminous pavements when wind velocities are low.

The particular friction factor of 0.26 is the mean value of the f's calculated by the above formula for each of the 41 plotted points. These values are shown in Table 1. An examination of these values indicates no marked change in friction factor at higher speeds as might be expected if lift were effective and there were no other compensating factors.

The curve designated as "Tolerable" in Fig. 10 is one which envelops nearly all the plotted points and was established on the basis of a constant friction factor of .20 in the formula

$$R = \frac{v^2}{15f}$$

For a particular speed, the radius should not be less than indicated by this curve otherwise skidding might occur.

The "Suggested Design" curve shown in Fig. 10 is expressed by a friction factor f of 0.17. This curve provides a margin of safety of 50 percent over the radii established by the "Limiting" curve. It is believed this margin of safety is necessary to account for the difference between the favorable conditions under which the tests were conducted and the more frequently encountered service conditions. The tests were conducted on dry pavement and surface winds were usually less than 15 mph. The effects of pavement condition, wind velocity and relative direction, tire condition, wing lift, distribution of weight on the landing gear, uncertainty of steering, and a host of similar factors were not evaluated separately in this investigation. Until the magnitude of these variables has been determined it seems a margin of safety of 50 percent is justified.

Conclusions

Within the limits of the tests, it was determined that type of landing gear and the size of the aircraft do not effect the speed-radius relationship.

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b. A friction factor of 0.3 means that the horizontal acceleration due to turning is 30 percent of g or 9.7 ft per sec.

For a given surface type, only speed has a significant effect on the limiting values of the radius of turning.

The suggested design curve for operation on dry bituminous pavements is shown in Fig. 10. Rounded values suggested for use as design radii are tabulated below:

Speed, mph	Radius, ft
10	50
20	150
30	350
40	650
50	1000

TABLE 1--COMPUTED FRICTION FACTORS "f"[c]

Aircraft	Speed, mph	Radius, ft	Friction factor, f
DC-3	17.6	100	0.21
	17.8	90	0.24
	22.9	120	0.29
	22.9	160	0.22
	26.8	180	0.30
	28.0	240	0.22
	28.1	180	0.29
	28.5	180	0.30
	28.8	240	0.23
	30.7	220	0.29
	31.2	180	0.36
	32.3	360	0.19
	33.5	220	0.34
	35.0	240	0.34
	40.9	320	0.35
DC-6	23.2	180	0.20
	25.7	220	0.20
	25.8	200	0.22
	27.2	180	0.27
	28.6	240	0.23
	31.1	320	0.22
	32.2	280	0.25
	33.1	280	0.26
	34.4	320	0.25
	36.7	280	0.32
	37.2	400	0.23
	37.5	360	0.26
	39.3	480	0.21
	43.1	480	0.26
	44.0	440	0.29
	44.9	520	0.26
	46.2	480	0.30
	47.1	560	0.26
	49.6	560	0.29
CV-340	19.5	100	0.25
	23.1	120	0.30
	29.6	200	0.29
	32.0	180	0.37
	36.8	480	0.19
	43.7	520	0.24
	44.7	480	0.28

c. Computed from formula $f = \frac{v^2}{15R}$

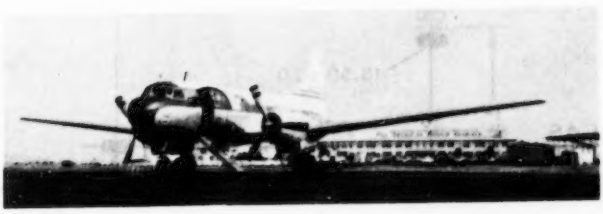
Acknowledgements

The authors wish to express their appreciation to United Air Lines, Inc. and the management of the San Francisco Airport for their cooperation in this investigation. Messrs W. E. Rhoades and J. D. Beaumont of United Air Lines made the arrangements for the use of the aircraft and Messrs H. C. Holloway and M. C. Casserly were the test pilots. Mr. F. W. Philpot, maintenance engineer, San Francisco Airport, and his staff assisted in laying out and painting the grid.

The authors also with to thank Professor R. A. Moyer of the University of California for his helpful suggestions throughout the test program and to Mr. Wayne Snowden of the Institute staff for his critical review of the manuscript.

DOUGLAS DC-3

DOUGLAS DC-6



CONVAIR CV-340

FIG. 1 - TEST AIRCRAFT

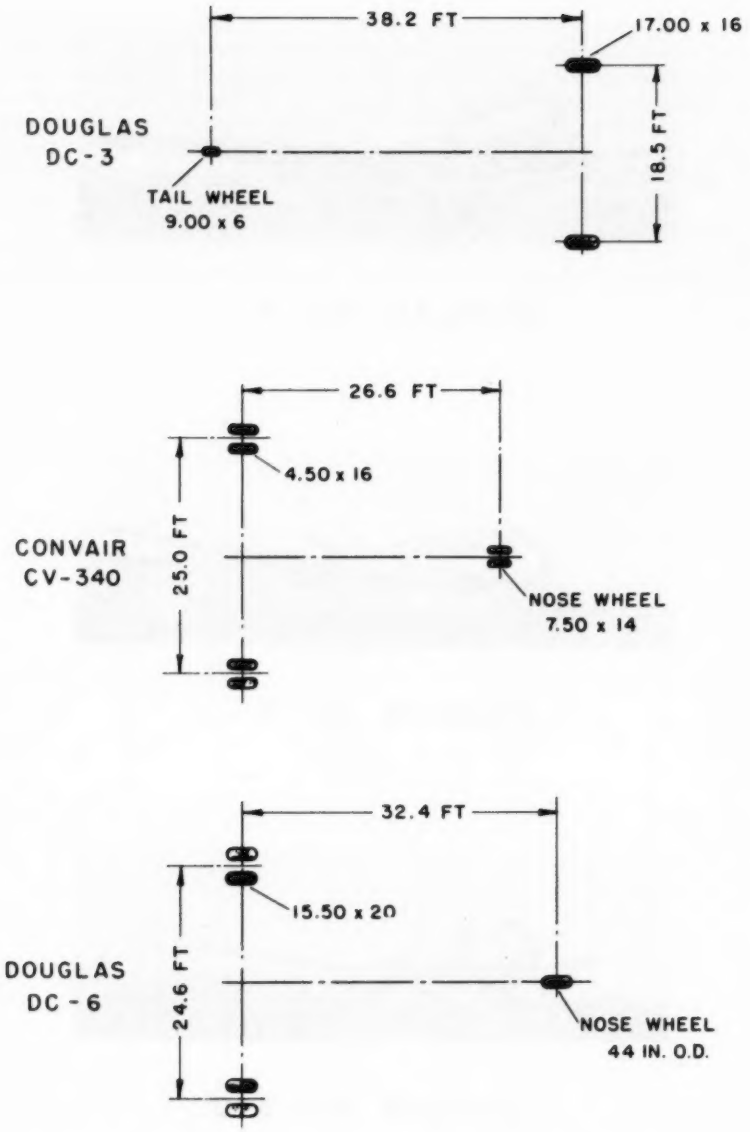


FIG. 2 - LANDING GEAR CONFIGURATIONS

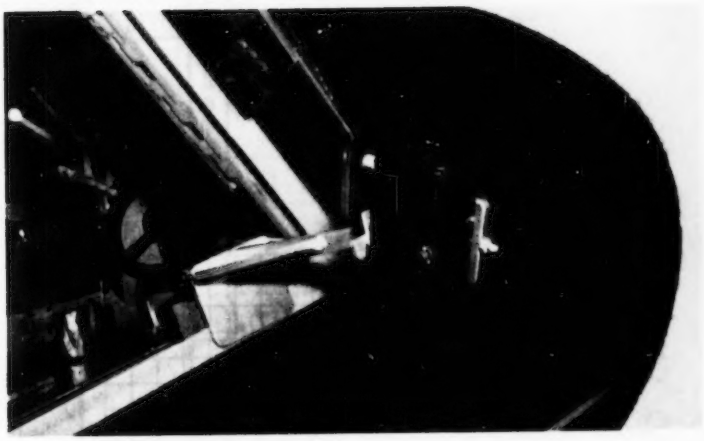


FIG. 3 - MOTION PICTURE CAMERA MOUNTED ON AIRCRAFT

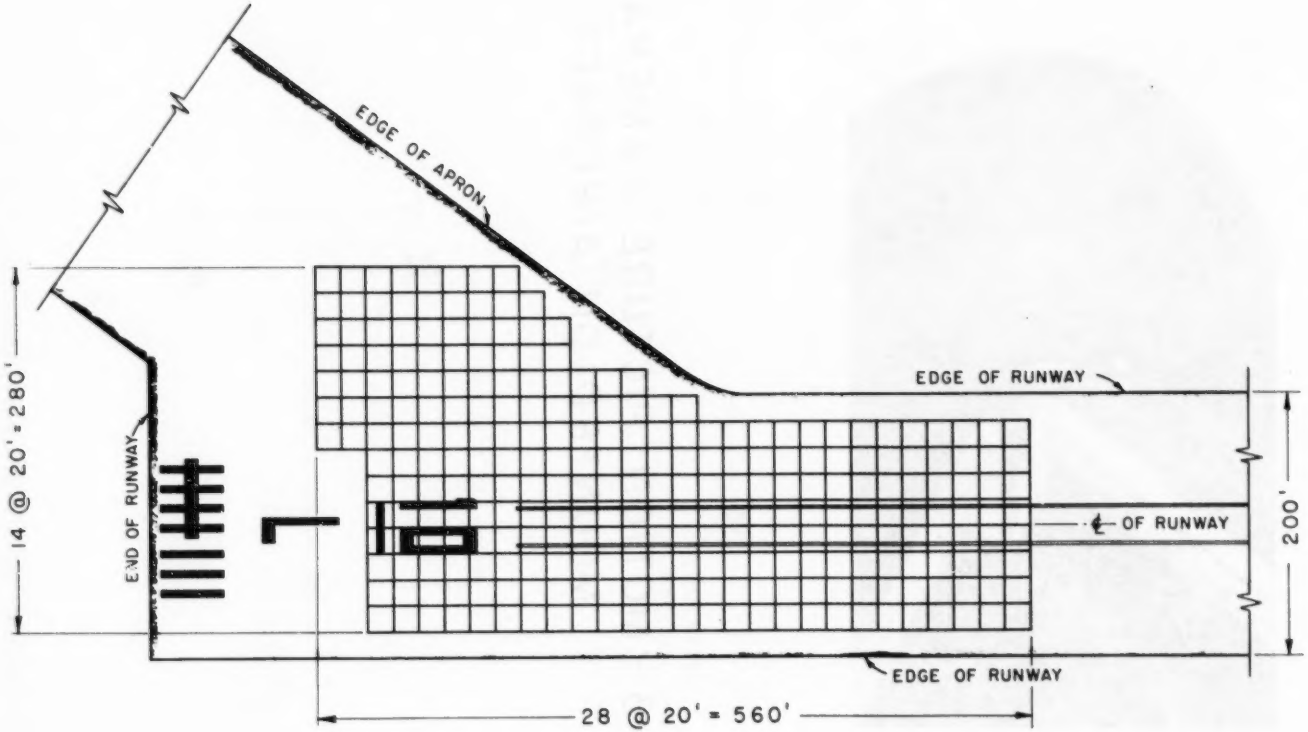


FIG. 4 GRID LAYOUT

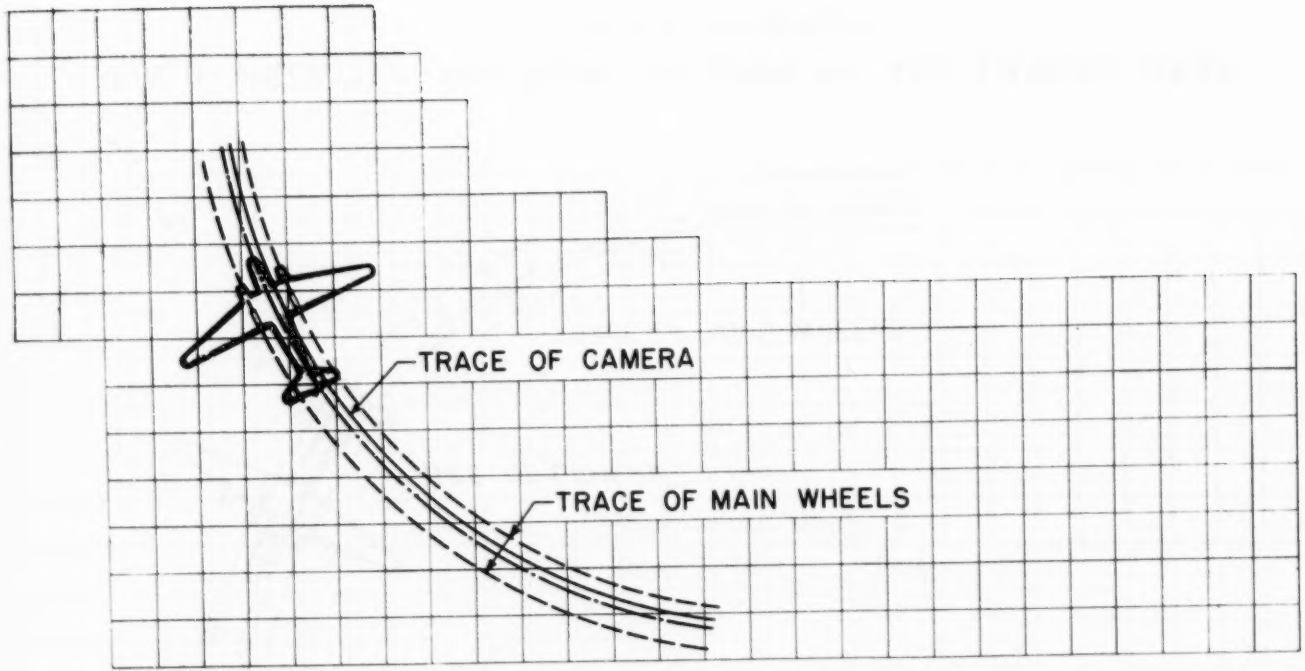


FIG. 5 - RELATIVE POSITIONS OF CAMERA AND LANDING GEAR
DC-3 AIRCRAFT

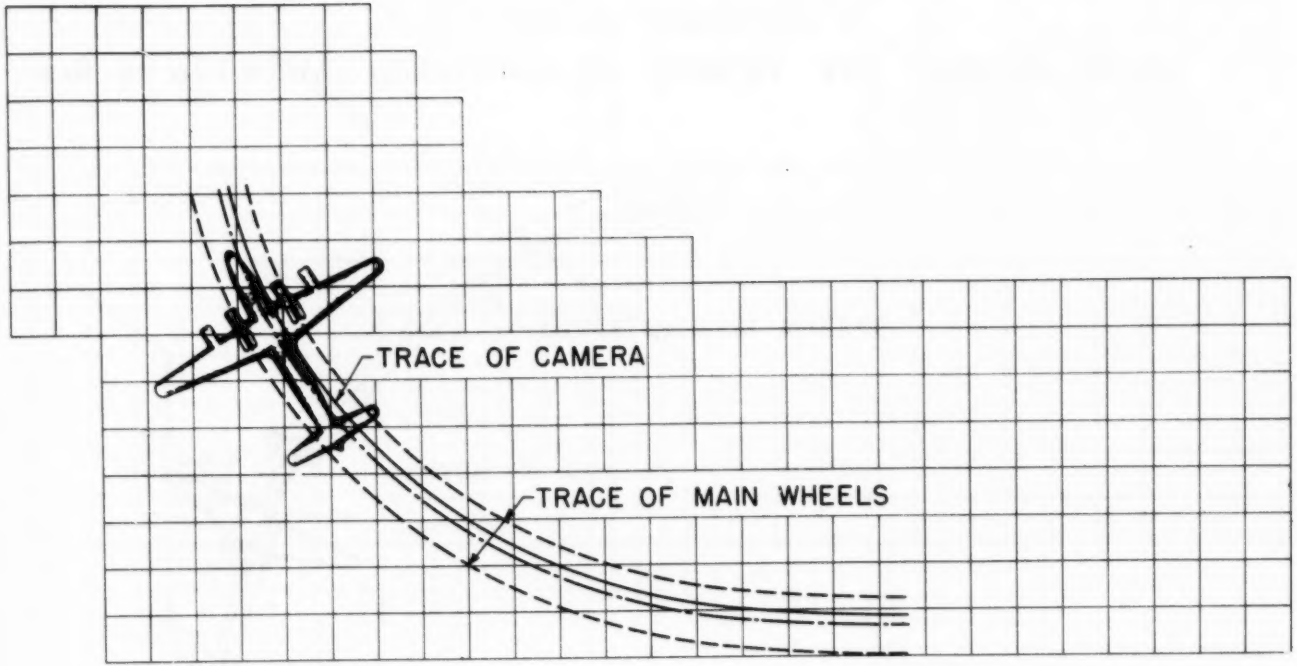


FIG. 6 - RELATIVE POSITIONS OF CAMERA AND LANDING GEAR
DC - 6 AIRCRAFT

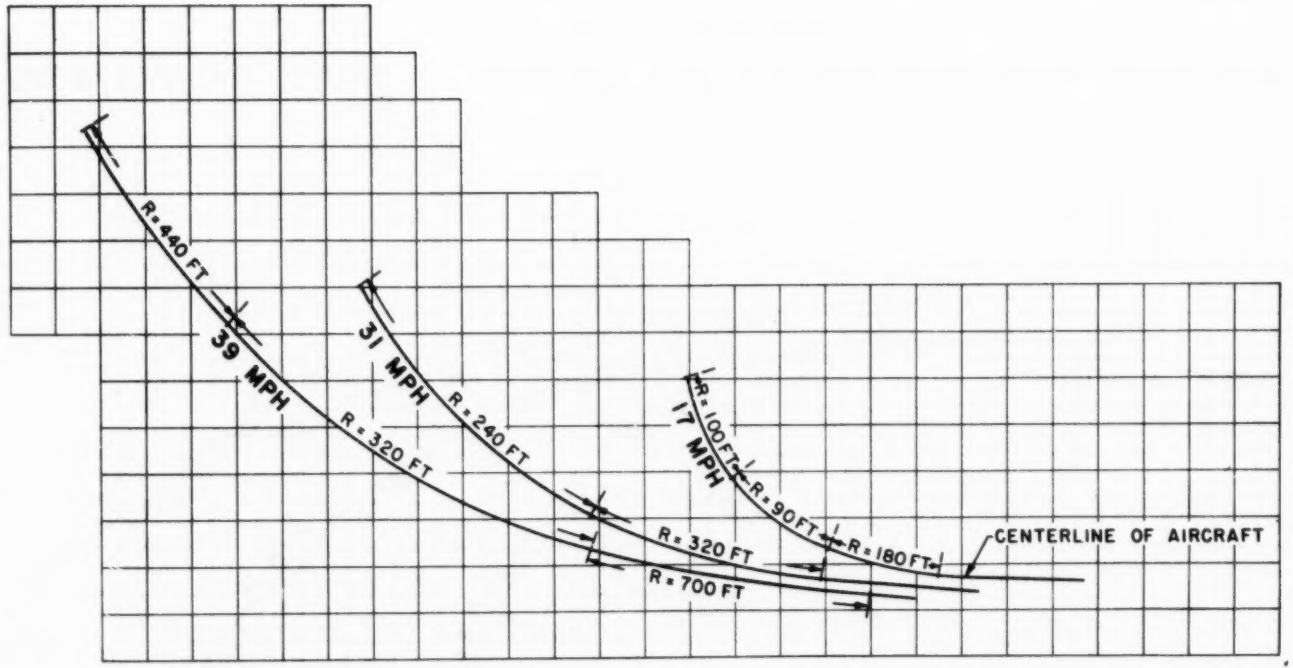


FIG. 7-TYPICAL TURNS AT VARIOUS SPEEDS, IMPENDING SKID CONDITIONS
DC-3 AIRCRAFT

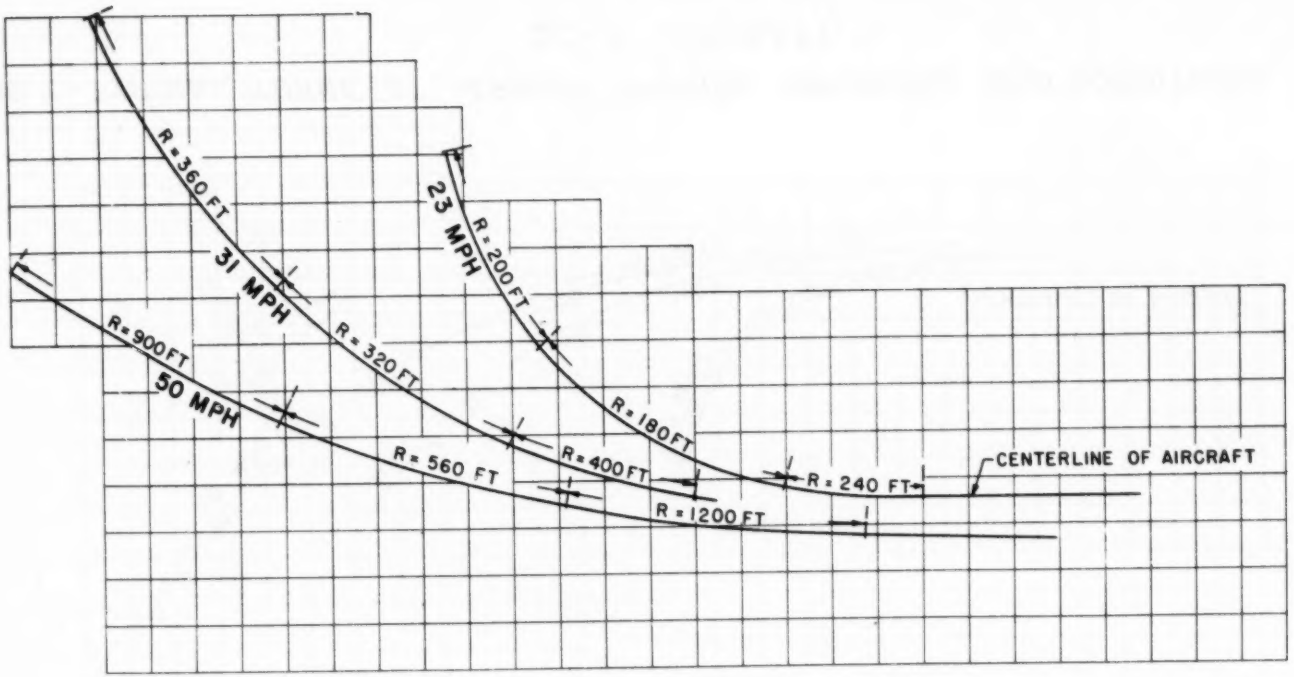


FIG. 8-TYPICAL TURNS AT VARIOUS SPEEDS, IMPENDING SKID CONDITIONS
DC-6 AIRCRAFT

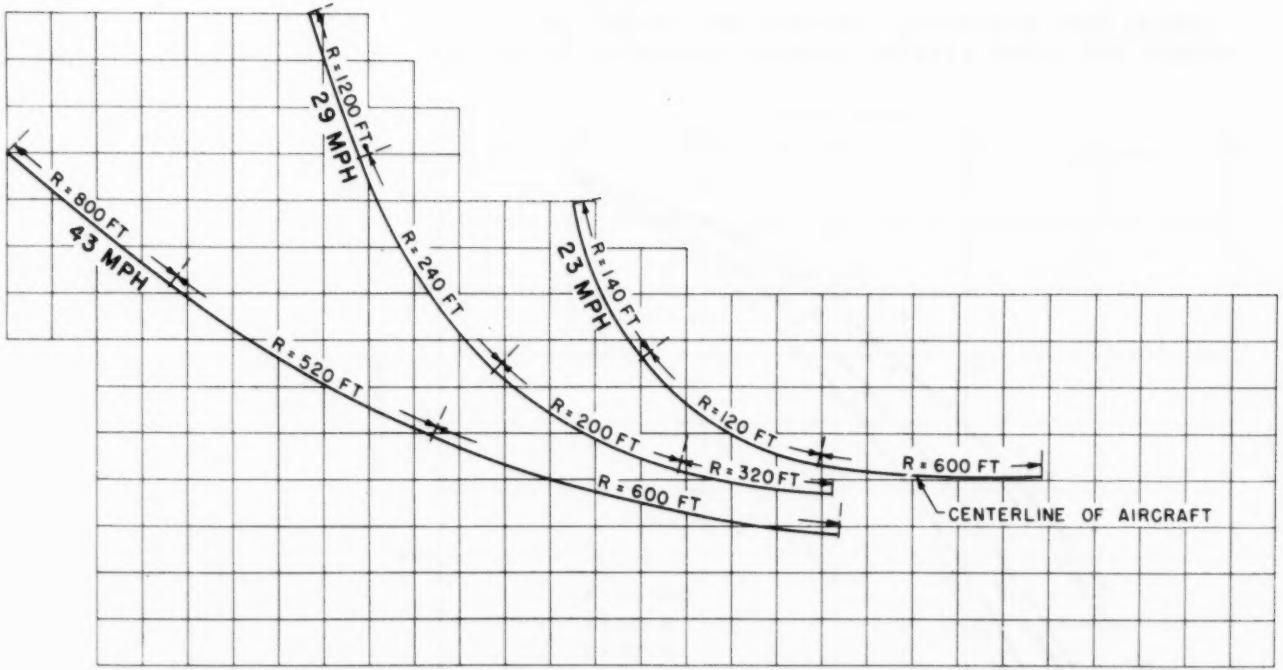


FIG. 9 - TYPICAL TURNS AT VARIOUS SPEEDS, IMPENDING SKID CONDITIONS
CV-340 AIRCRAFT

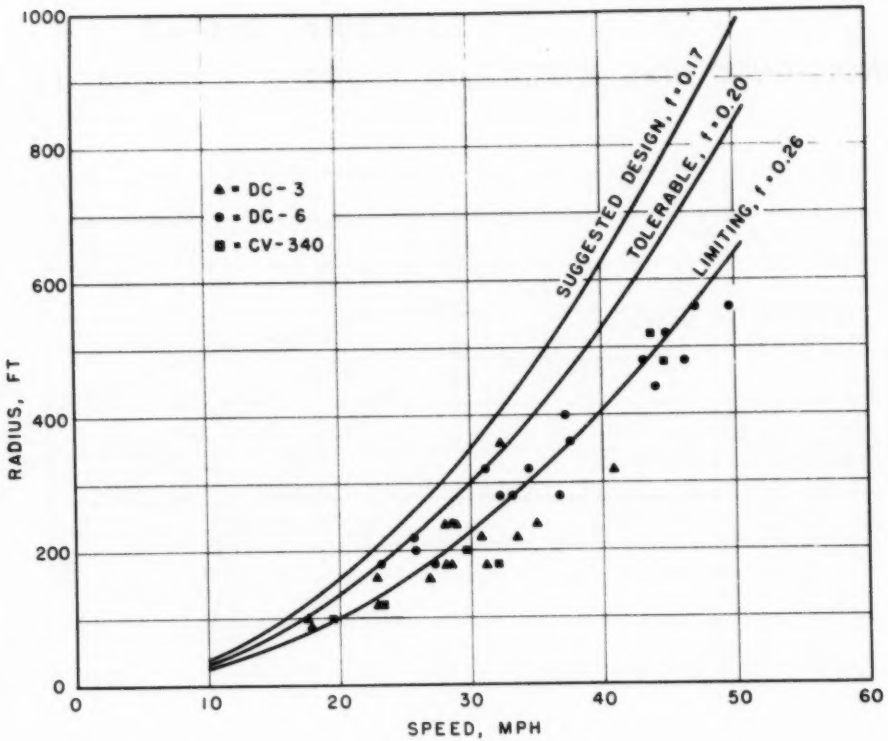


FIG. 10 - RELATIONSHIPS BETWEEN AIRCRAFT SPEED AND RADIUS OF TURNING FOR LIMITING, TOLERABLE, AND DESIGN CONDITIONS.

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